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EFFECTS OF AERATION ON SUCTION PRESSURE IN A SUBMERGED MEMBRANE BIOREACTOR

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Abstract—A membrane bioreactor (MBR) is one of the application of membrane technology to wastewater treatments. A submerged MBR is a type of MBR in which membrane modules are directly submerged into a bioreactor. Because the uplifting air flow is assigned the role of cake removal in a submerged MBR, aeration could affect the cake-removing efficiency and hence suction pressure. This study, therefore, examined the effect of aeration on cake removal and suction pressure using a pilot-scale submerged MBR and concluded that aeration was a significant factor governing the filtration conditions. Judging from the observed flow velocity of uplifting air measured with an electromagnetic flow velocity meter, cake-removing efficiency of the uplifting air flow was affected by the turbulence of the flow. The cake-removing efficiency was improved either (1) by augmenting an air flow rate or (2) by augmenting aeration intensity (an air flow rate per unit floor area) by concentrationg membrane modules over a smaller floor area. © 1997 Elsevier Science Ltd. All rights reserved

Key words—membrane bioreactor, micro-filtration, hollow fiber membrane, aeration, suction pressure, cake removal

INTRODUCTION

Recent advancement in membrane technology, especially in micro- and ultra-filtration, has given an impetus to the development of membrane bioreactors for various wastewater treatments. A membrane bioreactor (MBR) is the combination of a membrane module and a bioreactor. The allocation of the two compartments categorizes MBRs into a crossflow type and a submerged type (Fig. 1) (Yamamoto, 1994). In a crossflow MBR, a membrane module is allocated outside a bioreactor and mixed liquor is driven into the membrane module. On the other hand, in a submerged MBR, a membrane module is submerged into a bioreactor and mixed liquor is generally suctioned from the effluent side. The cake layer was often removed by the uplifting flow of bubbling air.

A submerged MBR is superior to a crossflow MBR in regard to the power consumption because suction pressure in a submerged MBR is generally lower than that in a crossflow MBR and because power consumption of recirculation pumps is absent in a submerged MBR (Yamamoto, 1989). A submerged MBR, therefore, has the potential to be applied to small wastewater treatment plants that need low cost treatment systems. This study, interested in cost saving systems, confined analysis to the submerged MBR.

After suction is continued in a bioreactor, a cake layer may accumulate on membrane surface, which often leads to suction pressure increase. To keep suction pressure stable therefore, two kinds of countermeasures for cake removal are generally undertaken. One is the continuous measure such as crossflow filtration. The other is the intermittent measure such as membrane washing with chemicals. In this study, the emphasis was placed on the former.

In a crossflow MBR, crossflow velocity partly governs suction pressure and permeation flux (Baker *et al.*, 1985; Riesmeier *et al.*, 1987; Magara *et al.*, 1991). On the other hand, in a submerged MBR, flow velocity of uplifting air corresponds to the crossflow velocity. The main aim of this study, therefore, was to examine the effect of aeration on suction pressure.

MATERIALS AND METHODS

Apparatus

A pilot-scale membrane bioreactor was used in this study (Fig. 2). The system basically consisted of a bioreactor, which had a working volume of 21.4 m^3, and membrane modules submerged into it. This plant was supplied with domestic wastewater from rural settlements. Raw sewage was supplied into the aeration tank after screening with a 1 mm bar screen.

Solid/liquid separation apparatus consisted of 42 hollow fiber membrane modules, which were made of polyethylene, and had a pore size of 0.1 μm and a filtration area of 4 m^2

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(Mitsubishi Rayon Co. Ltd). Two to four membrane modules were assembled vertically to consist of a "membrane unit", which was in turn connected to a suction pump. The suction pressure was controlled automatically to keep a constant flux of treated water.

The cake layer was removed by a sheering stress generated by the uplifting flow of bubbling air. The air was supplied by diffusers installed under the membrane modules. The bubbling air, therefore, had two roles in this system: supply of oxygen to activated sludge and removal of cake layer on membrane surface.

The operation was continued for 336 days, which were divided into two periods in terms of membrane module arrangement (Table 1). From the start to the 294th day of operation, 42 membrane modules were allocated to 18 membrane units. These units, in turn, were arranged in the matrix of six rows and three columns (horizontal section of Fig. 2). The air was supplied by 18 diffusers placed under each unit.

After the 295th day, membrane modules were rearranged in 12 membrane units by transferring 12 modules (nos 31–42, Table 1). Consequently, the 5th and 6th rows of the matrix were vacated and a floor area upon which modules were placed was reduced from 1.71 to 1.14 m^2.

Accordingly, the air valves to 6 diffusers (in the 5th and 6th rows in Fig. 2) were shut off in order to concentrate air supply from the remaining 12 diffusers. Aeration intensity (an air flow rate per unit floor area upon which the modules were placed), therefore, was increased one and half times (from 0.0068 to 0.0102 $m^3\ m^{-2}\ s^{-1}$) by rearranging the modules.

Operating conditions

Flux was maintained at 0.29 $m^3\ m^{-2}\ d^{-1}$ throughout the operation, excluding the case mentioned later. Intermittent suction method (8 min suction followed by 2 min rest, for instance) was applied. Hydraulic retention time was 13–16 h. The air flow rate of diffusers was fixed at 0.7 $m^3\ min^{-1}$ excluding the case mentioned later. MLSS was controlled roughly between 8000 and 12,000 mg L^{-1}. The average SRT was 125 days and the average BOD loading rate was 0.23 kg $m^{-3}\ d^{-1}$. The temperature of mixed liquor varied within the range of 14 and 29°C.

Membrane washing

Membrane washing was undertaken three times during the operation, taking every membrane unit outside the reactor. In the first washing (on the 252nd day of operation), tap water was blown against membrane modules to remove cake layer on membrane surface. In the second washing (on the 266th day), after treating with tap water as in the first washing, membrane modules were submerged into neutral detergent at 50°C for 16 h. In the third washing (on the 294th day), after treated with tap water as in the first washing, membrane modules were partly rearranged (Table 1).

Data collection and analysis

The data of trans-membrane pressure (simply called "pressure" hereafter), flux and air flow rates were collected automatically by sensors attached to the reactor. Therefore, all data on pressure and flux used in this paper were measured *in situ* in the reactor. The observed flux was adjusted to the data at 25°C by the following equation (Suzuki, 1987):

$$J_{25} = J_t \times \frac{\eta_t}{\eta_{25}}$$

where J_t is flux at t°C and η_t is the viscosity of pure water at t°C.

Total resistance of filtration was defined in this paper by the following equation:

$$R_t = \frac{p}{\eta_t \times J_t}$$

where R_t is total resistance, p is pressure, η_t is viscosity of the mixed liquor and J_t is flux.

The "observed" flow velocity of uplifting air was measured with an electromagnetic flow velocity meter (ACM-300, Alec electronics). The measuring site is shown in Fig. 2. The time constant of the flow velocity meter (Yuyama *et al.*, 1989) was set at 0.5 s.

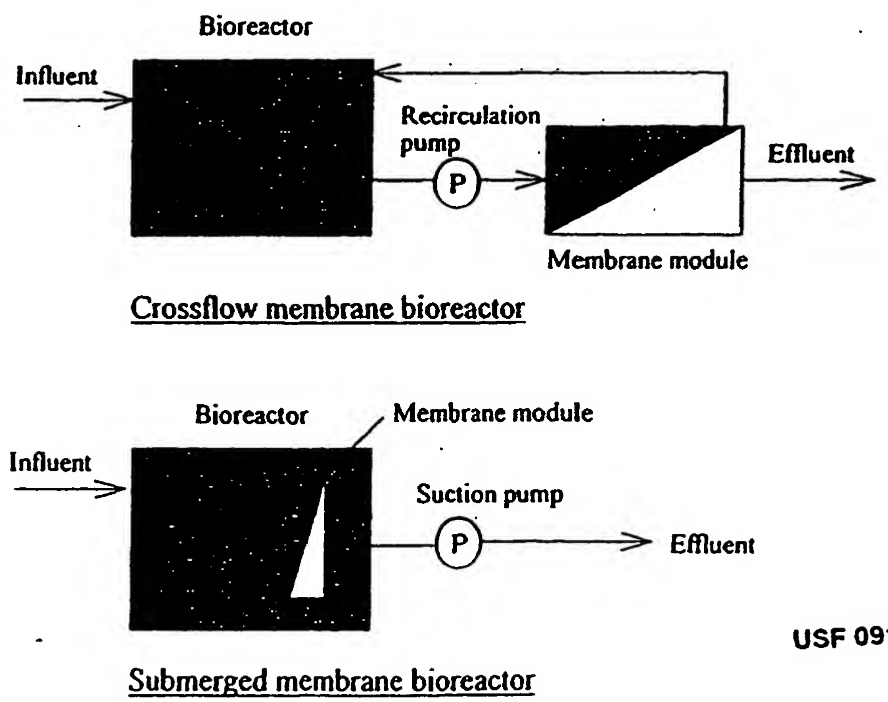

Fig. 1. Classification of membrane bioreactors (modified after Yamamoto, 1994).

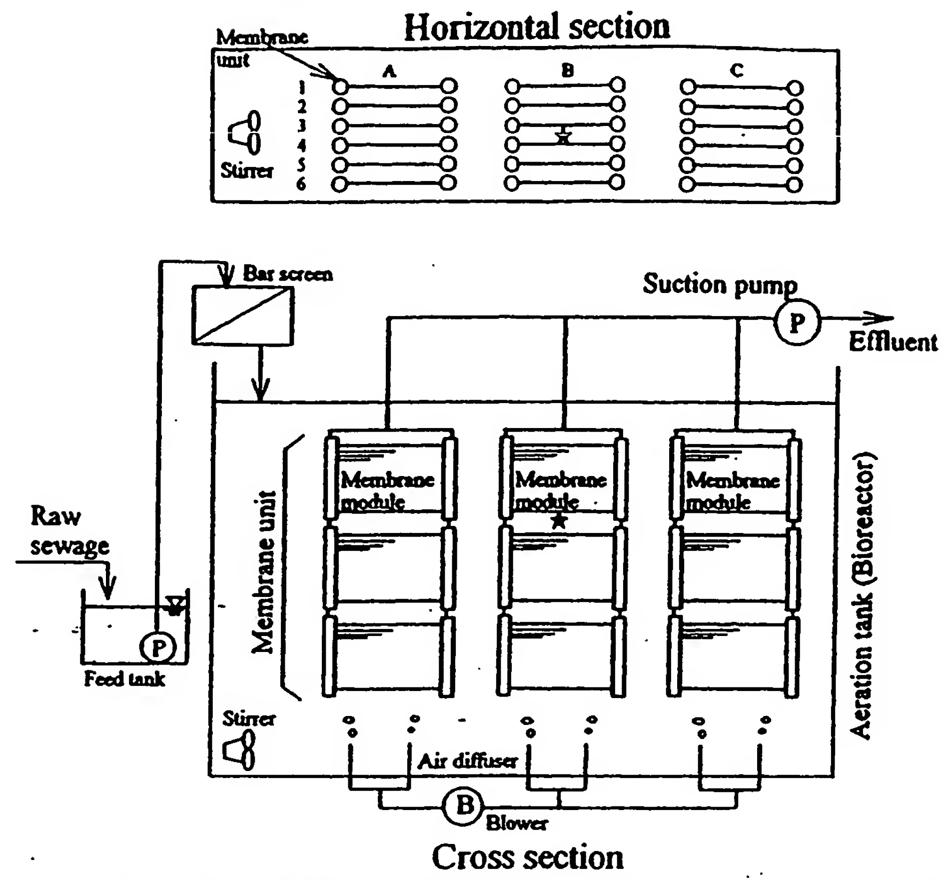

Fig. 2. Schematic diagram of the apparatus. ★ indicates the measuring site of flow velocity. In the diagram each membrane unit has 3 membrane modules for simplicity, but actually each unit has 2 to 4 modules.

RESULTS AND DISCUSSION

Air flow rate and cake removal

Fluctuation of the "observed" flow velocity of uplifting air is shown in Fig. 3. Although definition of the flow velocity in a two-phase (air–liquid) flow has not been established from the hydraulic viewpoint due to the complication of the flow (Goda *et al.*, 1965), this paper temporarily adopted "observed" flow velocity (simply called "flow velocity" hereafter) measured with an electromagnetic flow velocity meter. Because the flow velocity was measured just above two membrane modules (Fig. 2), the flow velocity meter recorded the uplifting flow after passing two modules. Because hollow fiber membranes are shaken by the uplifting flow, the turbulence of the uplifting flow may partly express how well the hollow fiber membranes are shaken. The shake of the hollow fiber membranes, in turn, is an important factor affecting filtration conditions (Fujita *et al.*, 1994). The turbulence of the flow, therefore, is supposed to affect filtration conditions.

Figure 4 shows the relationship between flux, pressure, flow velocity and air flow rates. Figure 4(a) shows that the inflection point of pressure was observed when the flux was set at 0.37 m d^{-1} and the air flow rate around 0.7 m^3 min^{-1}. On the other hand, Fig. 4(b) shows that the inflection point of the standard deviation of flow velocity roughly agreed with that of the pressure.

Table 1. Arrangement of membrane modules. Each of 42 modules is numbered and its arrangement is indicated in the matrix of membrane units (see the horizontal section of Fig. 2)

	Before module rearrangement				After module rearrangement		
	Column				Column		
Row	A	B	C	Row	A	B	C
1	1, 2, 3	4, 5, 6	7, 8, 9	1	1, 2, 3	4, 5, 6	7, 8, 9
2	10, 11, 12	13, 14, 15	16, 17, 18	2	10, 11, 12	13, 14, 15	16, 17, 18
3	19, 20	21, 22	23, 24	3	19, 20, 31, 32	21, 22, 33, 34	23, 24, 35, 36
4	25, 26	27, 28	29, 30	4	25, 26, 37, 38	27, 28, 39, 40	29, 30, 41, 42
5	31, 32	33, 34	35, 36	5	—	—	—
6	37, 38	39, 40	41, 42	6	—	—	—

Rearranged modules are underlined.

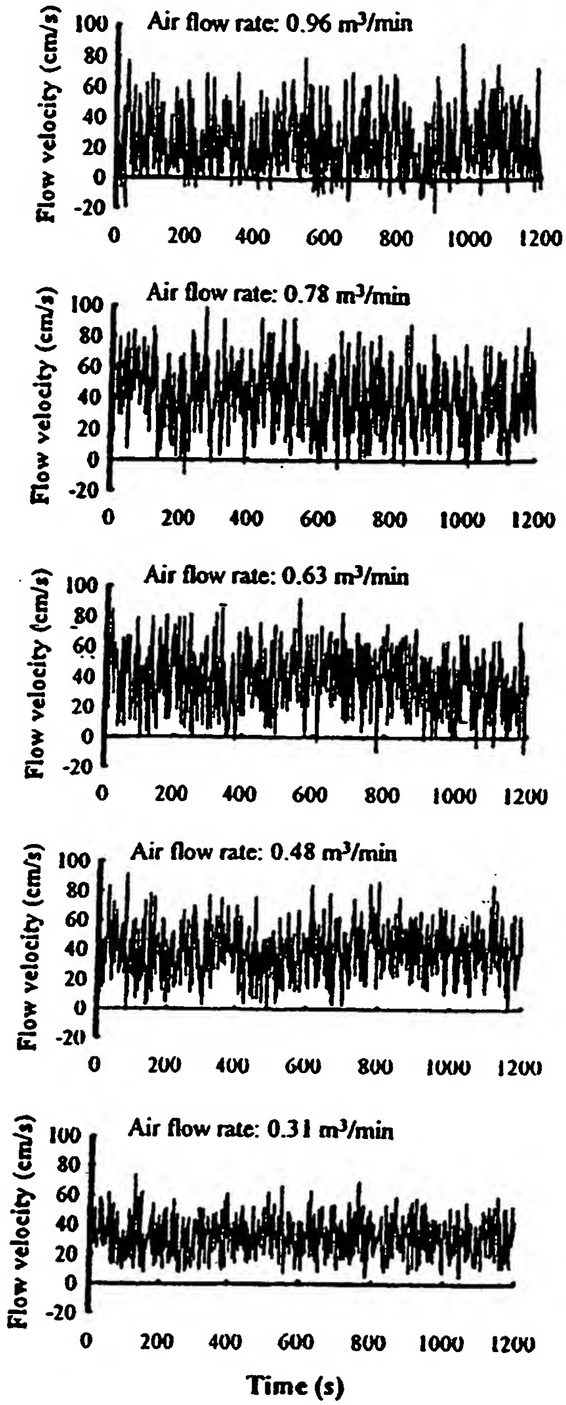

Fig. 3. Observed flow velocity of the uplifting air (measured on 141st day of operation.)

These suggest that the pressure was influenced by the turbulence of the flow. Besides, although pressure decreased according to the increase of the air flow rate below a certain critical value of the air flow rate (about 0.7 $m^3\ min^{-1}$ in this instance), the air-flow-rate increase had virtually no effect on pressure beyond the critical value. This implies that the cake-removing efficiency of aeration did not increase proportionally with the increase of an air flow rate and that the air flow rate had an optimum value (about 0.7 $m^3\ min^{-1}$ as mentioned above) from the cake-removing point of view. This optimum value may as well be determined as an operational air flow rate to avoid over-supply of air and to reduce power consumption, if oxygen supply to a bioreactor is sufficient.

Long-term effect of the air-flow-rate reduction

To examine the long-term effect of the air-flow-rate reduction on pressure, the air flow rate was reduced from 0.7 to 0.35 $m^3\ min^{-1}$ for 20 h (on the 330th day of operation) and was returned to 0.7 $m^3\ min^{-1}$ thereafter. Figure 5 shows the variation of pressure and air flow rates around the period. Corresponding to the reduction of the air flow rate, the pressure increased rapidly (Fig. 5(a)). The cake layer might develop in this period, for the reduced air flow rate might weaken cake-removing efficiency. After the air flow rate was restored, the pressure decreased slightly, but did not restore its former value. Thus the

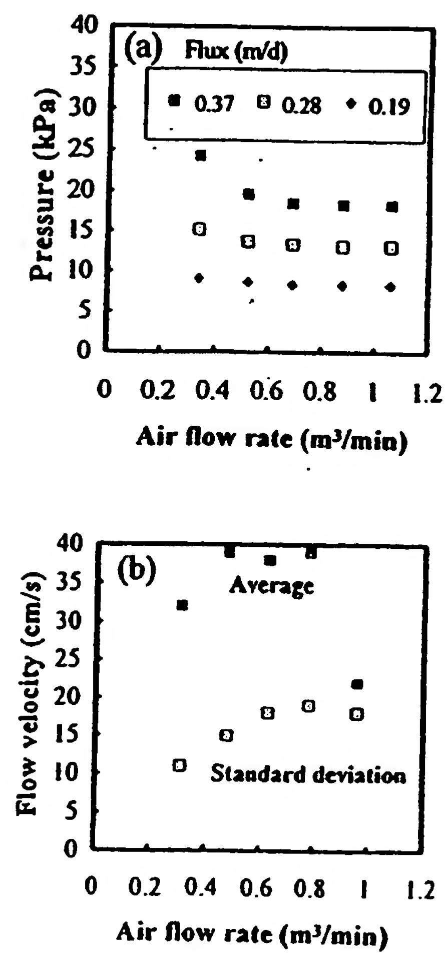

Fig. 4 (a) Suction pressure and (b) observed flow velocity versus air flow rate. The pressure was measured 8 min after the start of suction (measured on 141st day (b) and 280th day (a) of operation.)

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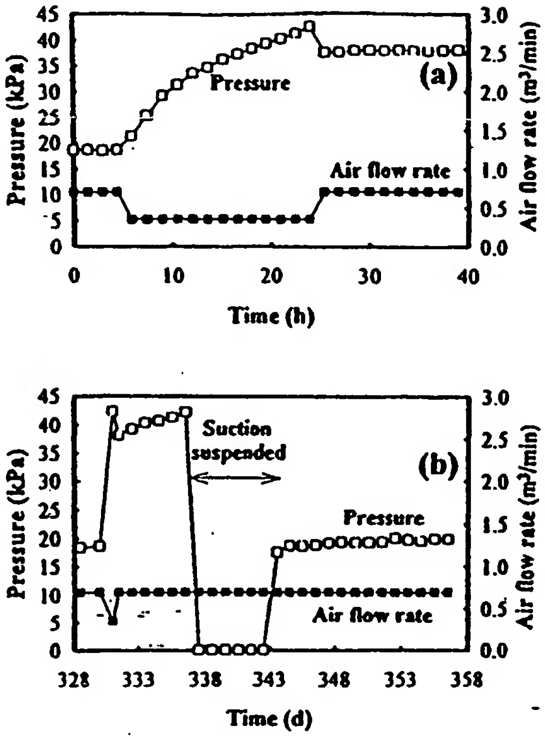

Fig. 5. Variation of suction pressure and air flow rate. The above figure (a) shows the variation from 330th to 331st day of operation. Suction was suspended from 336th to 343rd day of operation.

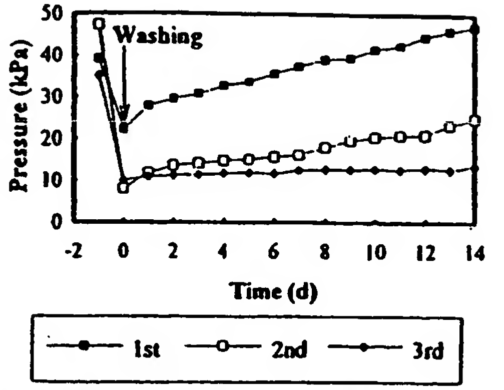

Fig. 6. Variation of suction pressure around membrane washing. Membrane washing was done one after another, but the time axis is plotted to each other for easy comparison.

long-term reduction of an air flow rate left considerable effect on pressure.

Five days after the air-flow-rate reduction, suction was suspended for 7 days while aeration was continued (Fig. 5(b)). When suction was resumed, the pressure restored the value before the reduction of the air flow rate. During the suction suspension, the cake layer might be removed successfully, because suspended solids in mixed liquor could not concentrate upon the membrane surface when suction was absent. This "aeration without suction" device could be used as a convenient way of on-site membrane washing without taking membrane modules outside a reactor.

Intensified aeration by module rearrangement

In the previous section, it was stated that the air-flow-rate increase had no effect on pressure beyond the critical value. However, cake-removing efficiency of an air flow might be improved without increasing an air flow rate, when the number of diffusers is reduced and the air flow is concentrated from the smaller number of diffusers. In this section, the effect of intensified or concentrated aeration was examined by rearranging membrane modules (Table 1) and by comparing the variation of pressure and total resistance after membrane washing.

Figure 6 shows the variation of pressure before and after membrane washing. Pressure, however, was affected by suction conditions, i.e. temperature and sludge viscosity, which varied somewhat in each washing period. Therefore, total resistance (R_t) increments in 2 weeks after the washing are also shown in Fig. 7 to cancel the influence of temperature and sludge viscosity. The relative R_t increments clearly shows the effect of intensified aeration applied after the third washing, because the R_t increment after the third washing was much smaller than that after the first and second washing.

Although the air flow rate was unchanged, rearrangement of modules after the third washing augmented aeration intensity (the air flow rate per unit floor area) one and half times (from 0.0068 to 0.0102 $m^3\ m^{-2}\ s^{-1}$). It was the augmentation of aeration intensity that stimulated the cake-removing efficiency after the third washing. Thus, the augmentation of aeration intensity was proved to be another way of the improvement of cake-removing efficiency. Therefore, it is useful to increase aeration intensity by concentrating modules over a smaller floor area, when designing a submerged MBR plant.

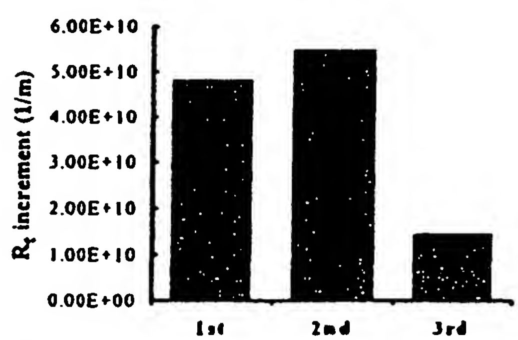

Fig. 7. Total resistance (R_t) increments in 2 weeks after membrane washing. The data was calculated by subtracting R_t at 10 minutes after washing from R_t 2 weeks after washing.

CONCLUSIONS

This study examined the effect of aeration on cake removal and suction pressure in a submerged membrane bioreactor. The data collected strongly indicated that aeration was the important factor governing the filtration conditions. The obtained results were summarized into the following four points:

(1) The cake-removing efficiency of the uplifting air flow was affected by the standard deviation of the flow velocity, that is, the turbulence of the flow.

(2) An increase in the air flow rate partly stimulated the cake-removing efficiency, but there was a critical value beyond which the air-flow-rate increase had virtually no effect on the cake-removing efficiency.

(3) Long-term (for 20 h) reduction of an air flow rate had a considerable effect on pressure.

(4) The cake-removing efficiency was improved by intensifying the air flow without increasing the air flow rate. Therefore, membrane modules are to be concentrated over a smaller floor area in order to augment the aeration intensity.

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(1) Fujita (2) Magara (3) Suzuki (4) Yamamoto (1994)
(5) Yuyama

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